

# New light on the Initial Mass Function of the Galactic Halo Globular Clusters

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## ABSTRACT

We present new constraints on the initial mass spectrum of the Galactic Old Halo globular clusters. This has remained poorly-known so far, as both an initial power-law mass spectrum and an initial lognormal mass function could have evolved into the presently observed globular cluster mass distribution, making the initial contribution of now lost low-mass objects ill-determined. Our approach consists in comparing the evolution with time of both the radial mass density profile and the number density profile of the globular cluster system. Using the analytical expression established by Vesperini & Heggie for the temporal evolution of the mass of a globular cluster on a circular orbit in a stable Galactic potential, we evolve the mass and number density profiles of many putative globular cluster systems, each starting with different initial cluster mass spectrum and initial cluster space-density. We then compare the modelled profiles with those of the Old Halo cluster system in order to investigate which system(s) provide(s) the best consistency with the data. Specifically, we build on the following points: (1) the presently observed mass density profile and number density profile of the Old Halo cluster system show the same shape, (2) assuming that globular clusters were initially distributed the same way in mass at all galactocentric distances, the mass and number density profiles had also the same shape initially, (3) according to our simulations, the mass density profile remains well-preserved, irrespective of the initial cluster mass spectrum, while the temporal evolution of its number counterpart depends sensitively on initial conditions. We show that to obtain a mass density profile and a number density profile which are identical in shape, both initially and after a Hubble-time of evolution, the globular cluster system must have been depleted in low-mass objects from the beginning. We deduce that the initial distribution in mass of the globular clusters was either a lognormal mass function, similar to that today, or a power-law mass spectrum with a slope  $\simeq -2$  and truncated at large mass, say, around  $10^5 M_\odot$ . In contrast, a power-law mass spectrum with a similar slope but extending down to low cluster mass (i.e., a few thousand solar masses) seems to be ruled out.

**Key words:** globular clusters: general – Galaxy: halo – Galaxy: formation

## 1 INTRODUCTION

Globular clusters are the oldest bound stellar systems in our Galaxy. Their study provides therefore valuable information about early Galactic evolution. In this respect, a major problem is that we do not know whether what we presently observe is still representative of the initial conditions and, thus, a fossil imprint of the formation process, or whether the initial conditions have been wiped out by a 13 Gyr long evolution within the tidal fields of what is now the Milky Way. Modelling the dynamical evolution of the Galactic globular cluster system is thus of great interest as it helps us to go

back in time to the earliest stages of the cluster system and to disentangle the formation and evolutionary fingerprints (see, e.g., Okazaki & Tosa 1995, Baumgardt 1998, Vesperini 1998, Fall & Zhang 2001). In spite of numerous efforts however, the shape of the initial distribution in mass of the halo globular clusters has remained ill-determined so far.

In our Galaxy, the mass function of the halo clusters <sup>1</sup> (the number of clusters per *logarithmic* mass interval, which

<sup>1</sup> In what follows, we adopt the nomenclature of McLaughlin & Pudritz (1996). We call luminosity/mass *spectrum* the number of objects per *linear* luminosity/mass interval,  $dN/dL$  or  $dN/dm$ , while we refer to the luminosity/mass *function* to de-

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is proportional to the number of objects per magnitude unit) is bell-shaped and usually fitted with a gaussian (e.g., Ashman & Zepf 1998). However, the underlying mass spectrum (i.e., the number of objects per *linear* mass interval) is well described by a two-index power-law, with exponents  $\sim -2$  and  $\sim -0.2$  above and below  $\sim 1.5 \times 10^5 M_\odot$ , respectively (McLaughlin 1994). The peak of the gaussian function in fact coincides with the cluster mass at which the slope of the mass spectrum changes. The slope of the high mass regime is reminiscent of what is observed in interacting and merging galaxies where systems of young massive clusters show well defined power-law luminosity spectra (i.e.,  $dN \propto L^{-\alpha} dL$ ) with  $\alpha$  in the range 1.8 to 2 (see, e.g., Whitmore & Schweizer 1995, Whitmore et al. 2002). This observational fact gave rise to the popular idea that the initial mass spectrum of the halo clusters may have been a power-law with a similar slope.

However, the luminosity spectrum  $dN/dL$  constitutes a faithful mirror of the underlying mass spectrum  $dN/dm$  only if any variations of the mass-to-light ratio from cluster to cluster are small. This is true for any cluster system whose stellar initial mass function is invariant and whose cluster age range is small. This is roughly the case for the Galactic halo globular clusters. Their visual mass-to-light ratio ranges from  $\sim 1$  to  $\sim 4$  (see Pryor & Meylan 1993 and Parmentier & Gilmore 2001, their Fig. 1), partly reflecting different cluster dynamical evolutions. This may not be true for cluster systems formed in ongoing or recent starbursts. Their formation duration may be a significant fraction of the system's median age and, thus, age spread effects among the young star cluster population may not be negligible. Being an age related quantity, the cluster integrated mass-to-light ratio can no longer be considered as a constant even for an invariant stellar initial mass function. For instance, a system of young clusters with an age range of 3 to 300 million years shows variations in the cluster mass-to-light ratio as large as a factor of 20 (see, e.g., Bruzual & Charlot 2003). As a result, the shape of the luminosity spectrum may differ substantially from the shape of the mass spectrum (Meurer et al. 1995, Fritze v. Alvensleben 1998, 1999). To unveil the mass spectrum of young clusters therefore requires estimates of their *individual* mass-to-light ratio with, e.g., spectral synthesis models. However, the results have remained inconclusive so far: the young cluster system of the nearby starburst galaxy NGC 3310 displays a gaussian mass function (and, thus, a two-index power-law mass spectrum; de Grijs et al. 2003) while the young massive clusters located in the Antenna merger (NGC 4038/39) are distributed in mass according to a pure power-law with slope  $\sim -2$  (Zhang & Fall 1999). These contrasting results may be interpreted as evidence against the universality of the globular cluster initial mass function.

Whether the Galactic halo cluster system actually started with a power-law mass spectrum or with a gaussian mass function similar to the current one has remained a very puzzling issue since both evolve into the presently observed lognormal mass function. As for the initial power-law mass spectrum, this form gets severely depleted below

a turnover of  $\sim 1.5 \times 10^5 M_\odot$  due to the preferential removal of low-mass clusters through evaporation and tidal disruption, leading after a Hubble-time of evolution to the current two-index power-law mass spectrum (e.g., Okazaki & Tosa 1995, Baumgardt 1998). On the other hand, Vesperini (1998) demonstrated that the presently observed gaussian mass function represents a state of quasi-equilibrium, that is, the gaussian shape and its associated parameters (mean and standard deviation) are preserved during the entire evolution through a subtle balance between disruption of clusters and evolution of the masses of those which survive, even though a significant fraction of the clusters is destroyed. The globular cluster initial mass distribution may thus have been a gaussian mass function or it may have been a power-law mass spectrum. As a result, the low-mass regime cannot be recovered by studying the temporal evolution of the mass spectrum only.

Along with the issue of the mass spectrum, several studies dedicated to the dynamical evolution of the Galactic globular cluster system also address the evolution with time of the cluster radial *number* density profile  $n(D)$  (i.e., the number of clusters per unit volume in space as a function of Galactocentric distance  $D$ ). Yet, the temporal evolution of the radial *mass* density profile  $\rho(D)$  (i.e., the spatial distribution around the Galactic centre of the halo cluster system mass) is not discussed (e.g., Baumgardt 1998, Vesperini 1998). Considering the case of a power-law mass spectrum with slope  $-2$  and extending down to  $500 M_\odot$ , McLaughlin (1999) emphasized the relative robustness of mass-related quantities with respect to number-related quantities (see his equations 4-7). The fact that the total mass and the mass density profile of a cluster system are better indicators of the initial conditions than are the number of clusters and the number density profile will be further illustrated in our Section 3.

In contrast to the robustness of the mass density profile, the disparity in the results derived by Vesperini (1998) and Baumgardt (1998) regarding the temporal evolution of the number density profile is more puzzling. The presently observed spatial distribution of the Galactic halo clusters is centrally concentrated with the density varying as  $D^{-3.5}$  (Zinn 1985), except in the inner 3-4 kpc where the distribution flattens to something closer to an  $D^{-2}$  dependence. As this flattening is likely to result (at least partly) from the shorter time-scale for cluster disruption at smaller galactocentric distance, Vesperini (1998) assumes that the initial number density profile scales as  $D^{-3.5}$  through the whole halo extent. Evolving such a system up to an age of 15 Gyr, he concludes that the initial steepness of the distribution is preserved, except in the inner Galactic regions where the greater efficiency of cluster destruction processes flattens the profile, in agreement with the presently observed one. On the other hand, Baumgardt's (1998) results suggest that an initial slope of  $-3.5$  (i.e., a steepness similar to what it is now) is ruled out as this one leads to a final spatial distribution significantly flatter than what is observed. Accordingly, the initial distribution must have been steeper and an initial slope of  $\sim -4.5$  is required to match the present spatial distribution. It is worth pointing out however that, while Baumgardt (1998) builds on a power-law mass spectrum with a slope  $\alpha = -2$  and probing down to  $1000 M_\odot$  (i.e., a choice inspired by the luminosity spectrum of young

massive clusters in starbursts and mergers), Vesperini (1998) investigates the case of the equilibrium gaussian mass function (i.e., an initial mass function similar to the present one because its shape remains well-preserved). Thus, their divergence about the initial steepness of the number density profile is likely to arise from a different choice for the initial cluster mass function.

This also suggests that the mass and number density profiles evolve differently with time. While the former remains a reliable mirror of what it initially was, irrespective of the initial distribution in mass of the clusters (as we will confirm in Section 3), the steepness of the latter after a Hubble-time of evolution may depend sensitively on the initial mass spectrum. This leads us to consider the possibility that a comparison between evolved and observed profiles, in terms of mass and in terms of number, may help shed light on the initial mass range and/or the initial distribution in mass of the Galactic halo clusters. Actually, if we *assume* that, soon after their formation, globular clusters show the same mass range and the same mass spectrum, irrespective of their galactocentric distance, then the mass and number density profiles are initially identical in shape. On the other hand, the presently observed mass and number density profiles of the halo cluster system also show shapes that match each other (see, e.g., McLaughlin 1999). Therefore, the robustness of the mass density profile combined with (1) the uniformity in shape for the *presently observed* mass and number density profiles and (2) the assumed uniformity in shape for the *initial* ones implies that the initial mass spectrum of globular clusters was such that the number density profile has been preserved in spite of evolution in the radially-dependent tidal fields of the Milky Way.

The outline of the paper is as follows. In Section 2, we build the radial mass and number density profiles of the Old Halo cluster system and we compare their shape. In Section 3, we briefly describe the analytic model as obtained by Vesperini & Heggie (1997) which enables us to evolve the number and mass density profiles of a cluster system. We evolve various globular cluster systems with different initial mass functions and different initial spatial distributions. In Section 4, we then compare the model outcomes with the observations in order to derive new constraints on the initial mass function of the Old Halo clusters, as well as on their initial spatial distribution. Finally, we present our conclusions in Section 5.

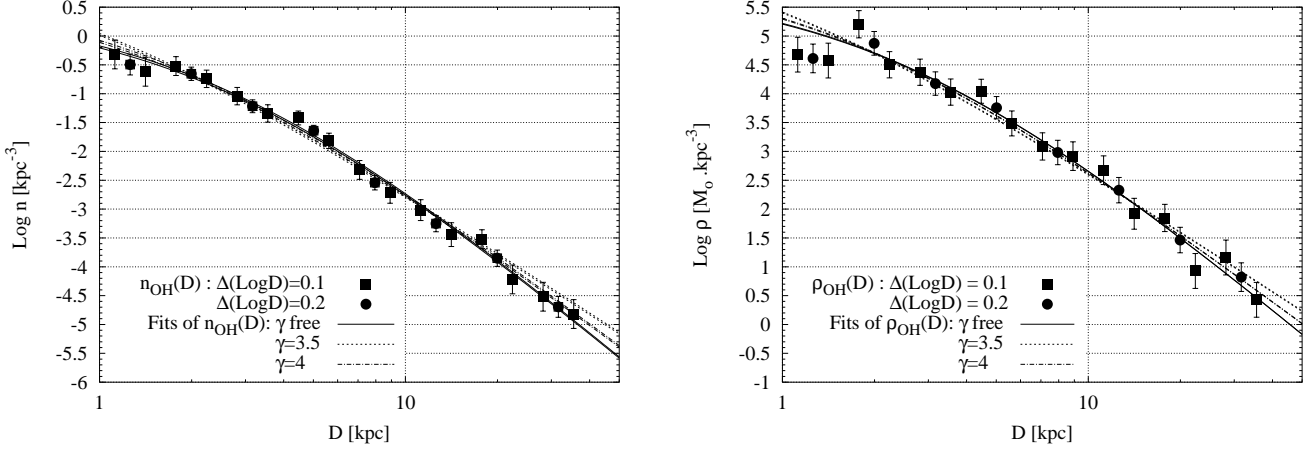
## 2 RADIAL PROFILES OF THE OLD HALO

Comparing the slopes of the mass density profile and of the number density profile, which is the core of this paper, is equivalent to studying the radial variation of the mean cluster mass (and, in fact, gives the physical reason for such a variation, namely, the possibly different responses to the dynamical evolution of the number-related and mass-related quantities). The observed radial variations of the mean cluster mass in the Milky Way, M31 and M87 have already been tackled by Gnedin (1997). Sorting the clusters in two equal size parts with respect to their galactocentric distance, he detected the existence of “statistically significant differences between the inner and outer populations, inner clusters being on average brighter than the outer clusters, as

would be expected if the inner population had been depleted by tidal shocks.” The dynamical interpretation of the results is presented in a complementary study by Ostriker & Gnedin (1997). However, his Milky Way sample does not discriminate among the different cluster populations, that is, disc/bulge, Old Halo and Younger Halo (see below). Due to obvious differences with respect to their age, their metallicity and their evolution history (i.e., accreted clusters have not been constantly subjected to the Galactic potential since the time of their formation), the interpretation of differences in the mean luminosity of the inner and outer populations may not be that straightforward. As for M87, the conclusions of Gnedin (1997) and Ostriker & Gnedin (1997) have been revisited by Kundu et al. (1999) who detected no significant variations of the cluster luminosity function turnover with respect to the projected galactocentric distance. Kundu et al. (1999) claimed that “the apparent brightening observed by Gnedin is probably due to undercompensation of completeness corrections in the inner regions, where the dimmer clusters are harder to detect against the strong galaxy background.” In contrast to Kundu et al.’s (1999) results, Barmby et al. (2001) found that the mean luminosity of the inner clusters of M31 is significantly brighter than that of the outer ones. However, they cautioned that variations driven by differences in cluster metallicity, age and stellar initial mass function may also be important and must be accounted for properly before using any luminosity function variation as a probe to differences in the globular cluster mass function.

In the present study, we restrict our attention to the Galactic globular cluster system. In the Galaxy only can we clearly discriminate among the different cluster populations regarding their age and evolutionary history. Specifically, we aim at constraining the initial mass spectrum of the first generation globular clusters which formed within the gravitational potential well of the Galaxy. Hence, we do not consider the more metal-rich, presumably second-generation, bulge/disc globular clusters (Zinn 1985). The halo cluster system itself hosts two distinct populations of clusters, the so-called Old Halo and Younger Halo (Van den Bergh 1993, Zinn 1993). The Old Halo globular clusters might have been formed ‘in situ’. In contrast, younger halo globular clusters are suspected of having been accreted. Regardless of their formation history, the Old Halo globular clusters form a coherent and well-defined group, well-suited to an analysis of their properties: thus, we consider the Old Halo subgroup only. Lists were initially compiled by Lee et al. (1994) and Da Costa & Armandroff (1995) and have recently been updated by Mackey & Gilmore (2004). We note in passing that, although coeval with the inner halo (Harris et al., 1997), we have not included NGC 2419 in our Old Halo sample. This cluster is located at a galactocentric distance of order 90 kpc and is thus unlikely to belong to the main body of the Galaxy. Moreover, van den Bergh & Mackey (2004) show that NGC 2419 and  $\omega$  Cen on the one hand, and the other halo clusters on the other hand, are at different loci in a half-light radius vs absolute visual magnitude diagram. This thus suggests that, as for  $\omega$  Cen (which we also exclude from our sample), NGC 2419 might be the tidally stripped core of a former dwarf spheroidal galaxy.

To build the mass and number density profiles, our source for the galactocentric distances  $D$  and the absolute



**Figure 1.** Left panel: fits of a power-law with a core (equation 1) to the number density profile of the Old Halo globular cluster subsystem. The different curves correspond to the parameter values given in Table 1. Right panel: the same curves (i.e., same core and same slope) are vertically shifted in order to match the Old Halo mass density profile. The good fit to the data in the right panel shows that the number and the mass density profiles of the Old Halo are indistinguishable in shape

**Table 1.** Results of fitting a power-law with a slope  $-\gamma$  and a core  $D_c$  (equation 1) on the observed number density profile of the Old Halo subsystem. The core and exponent derived for the number density profile are then directly applied to the mass density profile, the corresponding  $\chi^2$  and  $Q(\nu/2, \chi^2/2)$  being provided in the last two columns

$\Delta \text{Log} D$	$\text{Log}(n_0)$	$D_c$	$-\gamma$	$\chi^2$	$Q$	$\text{Log}(\rho_0)$	$\chi^2$	$Q$
0.1	$0.53 \pm 0.32$	$2.33 \pm 1.03$	$-4.50 \pm 0.53$	6.63	0.92	$5.92 \pm 0.06$	12.68	0.63
0.2	$0.49 \pm 0.33$	$2.33 \pm 1.08$	$-4.50 \pm 0.55$	4.53	0.48	$5.90 \pm 0.08$	4.74	0.69
$\gamma$ imposed								
0.1	$1.42 \pm 0.41$	$0.68 \pm 0.21$	-3.5	12.63	0.56	$6.79 \pm 0.06$	18.28	0.25
0.2	$1.38 \pm 0.42$	$0.69 \pm 0.22$	-3.5	10.06	0.12	$6.77 \pm 0.08$	7.87	0.34
0.1	$0.84 \pm 0.24$	$1.45 \pm 0.26$	-4.0	7.84	0.90	$6.22 \pm 0.06$	14.44	0.49
0.2	$0.80 \pm 0.25$	$1.46 \pm 0.27$	-4.0	5.63	0.47	$6.20 \pm 0.08$	5.64	0.58

visual magnitudes  $M_v$  is the McMaster database compiled and maintained by Harris (1996, updated February 2003). Cluster absolute visual magnitudes have been turned into luminous mass estimates by assuming a constant mass-to-light ratio  $M/L_v = 2.35$  (i.e., the average of the mass-to-light ratios of the halo clusters for which Pryor & Meylan (1993) obtained dynamical mass estimates). The Old Halo mass and number profiles are derived by binning the data with two different bin sizes:  $\Delta \log D = 0.1$  and  $0.2$  ( $D$  is in kpc), corresponding to 16 and 8 points, respectively. As for the size of the error bars, a Poissonian error on the number of clusters in each bin is combined with a fixed error on the mass-to-light ratio. In fact, not all globular clusters show the same mass-to-light ratio, the standard deviation in the Pryor & Meylan (1993) compilation being of order  $\sigma_{\text{Log}(M/L_v)} = 0.17$ .

As already mentioned, the observed radial distribution of halo clusters obeys  $D^{-3.5}$  except in the inner 3-4 kpc where the distribution gets shallower. As a result, it is often parametrized by a power law with a core (see equation 1). Previous fits having been obtained for either the whole Galactic globular cluster system (e.g., Djorgovski &

Meylan 1994) or the whole halo system (e.g., McLaughlin 1999), we now consider the Old Halo subsystem only. Using a Levenberg-Marquardt algorithm (Press et al. 1992), we fit the Old Halo number density profile with:

$$\text{Log} n(D) = \text{Log} n_0 - \gamma \text{Log} \left( 1 + \frac{D}{D_c} \right). \quad (1)$$

The values obtained for the slope  $-\gamma$  and the core  $D_c$  are presented in the left part of Table 1. For each fit, we also give the  $\chi^2$  and the incomplete gamma function  $Q(\nu/2, \chi^2/2)$  ( $\nu$  is the number of degrees of freedom) which provides a quantitative measure for the goodness-of-fit of the model<sup>2</sup>. Imposing a slope  $-\gamma$  of -3.5 or -4, as found by Djorgovski & Meylan (1994) for the whole globular cluster system, provides a good fit to the number density profile of the Old Halo cluster system as well. Keeping all three parameters free, we obtain a steeper slope ( $-\gamma \simeq -4.5$ ) coupled

<sup>2</sup> We remind the reader that: a  $Q$  value of 0.1 or larger indicates a satisfactory agreement between the model and the data; if  $Q \geq 0.001$ , the fit may be acceptable if, e.g., the errors have been moderately underestimated; if  $Q < 0.001$ , the model can be called into question (Press et al. 1992).

**Table 2.** Results of fitting a power-law  $D^{-\gamma}$  to the number and mass density profiles of the Old Halo subsystem, considering clusters with  $D \gtrsim 3$  kpc only, that is, focusing on regions which have been least affected by dynamical evolution

$\Delta \text{Log} D$	$\text{Log}(n_0)$	$-\gamma$	$\chi^2$	Q	$\text{Log}(\rho_0)$	$-\gamma$	$\chi^2$	Q
0.1	$0.83 \pm 0.17$	$-3.64 \pm 0.18$	5.00	0.83	$6.26 \pm 0.25$	$-3.66 \pm 0.24$	6.11	0.73
0.2	$0.68 \pm 0.15$	$-3.53 \pm 0.16$	4.66	0.32	$6.06 \pm 0.27$	$-3.46 \pm 0.26$	1.33	0.86

with a larger core. The core reflects the flattening of the spatial distribution at small galactocentric distances, presumably owing to the greater efficiency of disruptive processes. Ignoring this core region and focusing on the Old Halo clusters located at galactocentric distances  $\gtrsim 3$  kpc, that is, where memory of the initial conditions has perhaps been better preserved, we find that both the mass and the number density profiles of the Old Halo are well-approximated by pure power-laws with slope  $\simeq -3.5$  (see Table 2). The steepness of the Old Halo spatial distribution is thus similar to that of the whole halo (Zinn 1985). While the mass and number density profiles show very similar steepness at distances larger than 3 kpc, their overall shapes are also very similar. Fitting the Old Halo mass density profile with the same functions as used for the number density profile (i.e., equation 1 and the  $(\gamma, D_c)$  couples listed in Table 1) provides equally good values of the incomplete gamma function (see the last column of Table 1). Therefore, the number and the mass density profiles of the Old Halo are indistinguishable through the whole extent of the halo.

### 3 EVOLVED RADIAL DENSITY PROFILES OF GLOBULAR CLUSTER SYSTEMS

The previous section shows that the *currently observed* mass density and number density profiles of the Old Halo are identical in shape. If we *assume* that the globular cluster formation mechanism produced the same mass range and the same mass spectrum for the clusters, irrespective of their galactocentric distance, then the *initial* mass and number density profiles were identical in shape as well. If the mass density profile has been preserved (and we show in this section that it is actually the case), all together, these facts imply that the number density profile itself has remained fairly unaltered during evolution in the tidal field of the Milky Way. In what follows, we evolve various putative globular cluster systems, considering different combinations of initial mass spectra and initial spatial distributions. We then investigate in which case(s) has the number density profile been reasonably preserved. We also compare in a least-squares sense the evolved spatial distributions to the observed ones that we have derived in Section 2.

To evolve the radial mass and number density profiles of a cluster system from the time of its formation up to an age of 15 Gyr, we adopt the analytic formula of Vesperini & Heggie (1997) which supplies at any time  $t$  the mass  $m$  of a star cluster with initial mass  $m_i$  which is moving along a circular orbit perpendicular to the galactic disc at a galactocentric distance  $D$ . The assumption of circular orbits is clearly a simplifying one since it implies that the time varia-

tions of the tidal field for clusters on elliptical orbits are not allowed for in our calculations. Yet, the system of relevance here is the Old Halo. This shows less extreme kinematics than the Younger Halo group of clusters, making this assumption less critical than if we have dealt with the whole halo system. As for the influence of the cluster orbit inclination with respect to the Galactic disc, Murali & Weinberg (1997) found that, although low-inclination halo clusters evolve more rapidly than high-inclination ones, the differences are not extreme. Furthermore, our sample excluding disc clusters, the assumption of high inclination orbits is a reasonable one. The simulations of Vesperini & Heggie (1997) were designed in the frame of a host galaxy modelled as a simple isothermal sphere with a constant circular velocity. This actually constitutes a reasonable assumption for the Old Halo system whose radial extent is 1-40 kpc, that is, where the mass profile of the Milky Way (i.e., the total Galactic mass enclosed within a radius  $D$ ) grows linearly with the galactocentric distance (Harris 2001). We consider the effect of non-circular orbits in more detail in Section 4, below.

The relations describing the temporal evolution of the mass of a globular cluster have been obtained by fitting the results of a large set of N-body simulations in which Vesperini & Heggie (1997) take into account the effects of stellar evolution as well as two-body relaxation, which leads to evaporation through the cluster tidal boundary. Disc shocking can also be included (see below). In order to take into account dynamical friction, globular clusters whose time-scale of orbital decay (see, e.g., Binney & Tremaine 1987) is smaller than  $t$  are removed from the cluster system at that time (see Vesperini 1998, his Section 2, for further details). It is important to note a specific assumption underlying the validity of this analysis. The large-scale Galactic gravitational potential is assumed constant, that is, this model considers the evolution of a globular cluster system only after it has been assembled in a time-independent Galaxy. That is the physical basis for a restriction to the system of Old Halo globular clusters.

The temporal evolution of the mass of a cluster orbiting at constant galactocentric distance  $D$  is found to follow:

$$\frac{m(t)}{m_i} = 1 - \frac{\Delta m_{st, ev}}{m_i} - \frac{0.828}{F_{cw}} t. \quad (2)$$

$\Delta m_{st, ev}/m_i$  is the fraction of cluster mass lost due to stellar evolution (18 per cent in this particular model). The time  $t$  is expressed in units of 1 Myr and  $F_{cw}$ , a quantity proportional to the initial relaxation time, is defined as:

$$F_{cw} = \frac{m_i \times D}{\ln N}, \quad (3)$$

where  $m_i$  and  $D$  are in units of  $1 M_\odot$  and 1 kpc, respectively, and  $N$  is the initial number of stars in the cluster.

**Table 3.** Fraction  $F_N$  of surviving clusters and ratio  $F_M$  of the final to the initial mass in clusters after a 15 Gyr long evolution for globular cluster systems with various initial spatial distributions  $n_{init}(D)$  and cluster initial mass functions/spectra (CIMF/Sp). G refers to a gaussian mass function  $dN/d \log m$  with a mean  $\log m_0 = 5.03$  and a standard deviation  $\sigma = 0.66$  (i.e., the equilibrium mass function as defined by Vesperini 1998). PL5, PL4 and PL3 refer to power-law mass spectra  $dN/dm$ , with a slope  $\alpha = -1.9$  and extending down to  $1E5 M_\odot$ ,  $1E4 M_\odot$  and  $1E3 M_\odot$ , respectively. Results are presented with (DS) and without (no DS) disc shocking included in the simulations

$n_{init}(D)$	CIMF/Sp	no DS		DS	
		$F_M$	$F_N$	$F_M$	$F_N$
$D^{-3.5}$	G	0.54	0.62	0.50	0.56
	PL5	0.55	0.87	0.51	0.77
	PL4	0.39	0.32	0.36	0.30
	PL3	0.30	0.05	0.28	0.04
$D^{-4.5}$	G	0.37	0.43	0.31	0.35
	PL5	0.38	0.72	0.32	0.55
	PL4	0.24	0.14	0.20	0.11
	PL3	0.19	0.02	0.15	0.01

To take into account disc shocking, the factor  $0.828/F_{cw}$  is merely replaced by  $\lambda$  as defined by equation (3) of Vesperini (1998).

We have distributed 20,000 clusters following various radial and mass distributions. Four different initial distributions in cluster mass have been considered:

- a) a gaussian mass function  $dN/d \log m$  with parameters equal to those of the equilibrium mass function of Vesperini (1998), that is, a mean  $\log m_0 = 5.03$  and a standard deviation  $\sigma = 0.66$ ;
- b) three power-law mass spectra  $dN/dm$ , each with a slope of  $-1.9$  and different lower mass limits, namely,  $1E3$ ,  $1E4$  and  $1E5 M_\odot$ . The value of the slope agrees with what is obtained for the high mass regime of the Galactic halo cluster system, that is, a slope of around  $-1.8$  to  $-2$  (see, e.g., Ashman & Zepf 1998).

As for the last low-mass cut-off, Fall & Zhang (2001) indeed show that the cluster mass spectrum may have started with a truncation at mass of order  $1E5 M_\odot$ , the low-mass tail of the present mass distribution resulting from the evaporation of initially more massive clusters located close to the Galactic centre. This illustrates one more time the difficulty of deducing the initial distribution in mass of the globular clusters on the sole ground of evolving it with time. Three different initial mass spectra manage to evolve into the presently observed bell-shaped mass function: (1) a power-law probing down to  $1000 M_\odot$  or (2) truncated at  $10^5 M_\odot$  as well as (3) a two-index power-law with a turnover around  $10^5 M_\odot$ . We thus are ignorant of the contribution of the low-mass objects to the initial population of globular clusters. Did they constitute the overwhelming contribution by number (case 1), were they missing (case 2), or were they present in limited number (case 3) ?

Regarding the initial number density profile (equiva-

lent in shape to the initial mass density profile following our assumption of a unique mass range and a unique mass spectrum through the Old Halo extent), we assume two different functional forms:

- a)  $n(D) \propto \rho(D) \propto D^{-3.5}$ , as suggested by our fits to the observed spatial distributions for globular clusters located beyond 3 kpc (see Table 2);
- b)  $n(D) \propto \rho(D) \propto D^{-4.5}$  (Baumgardt 1998).

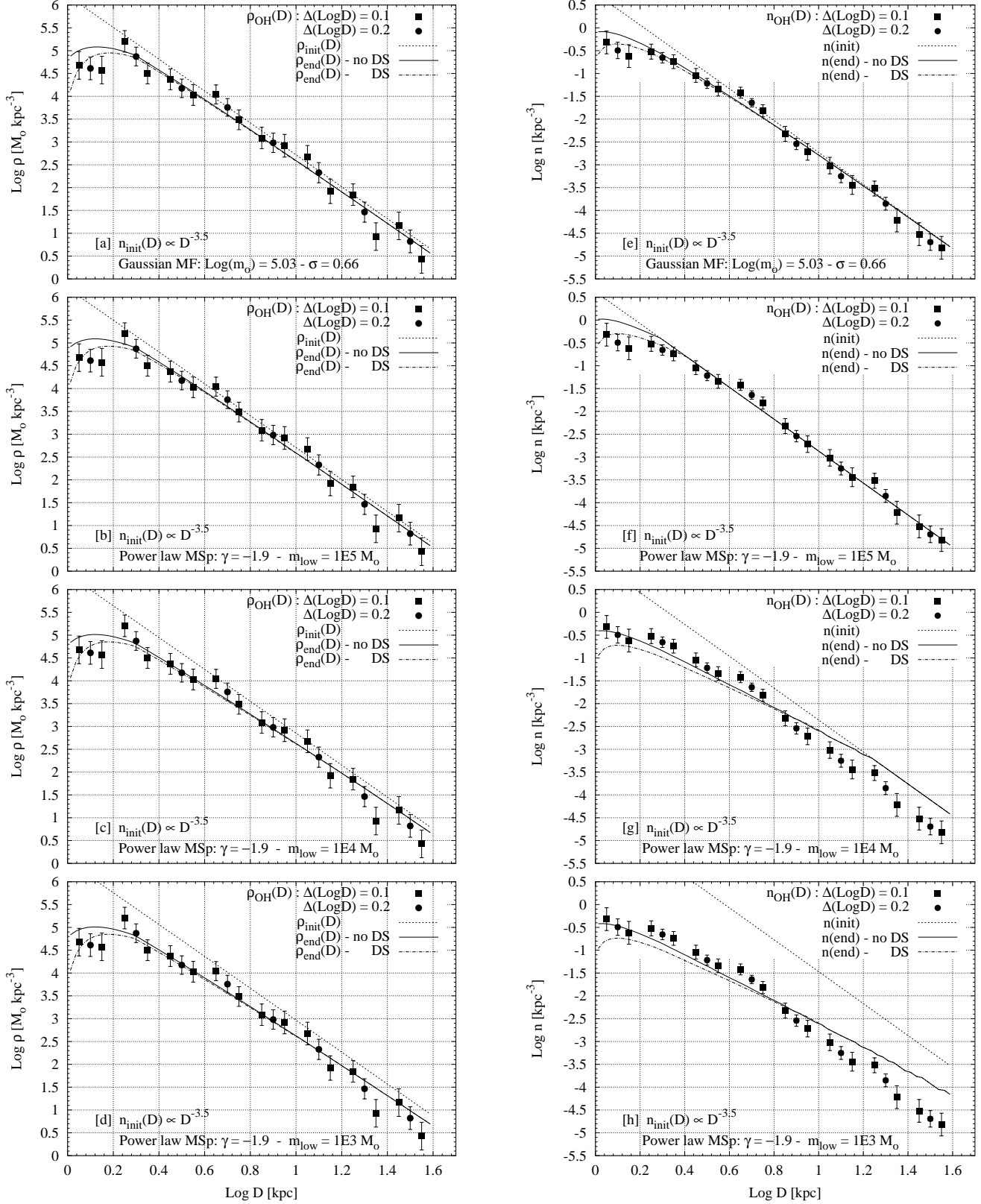
We have thus considered a total of 16 different cases, combining the 4 different initial mass spectra/functions with the 2 different initial spatial-densities and including or not disc shocking.

Table 3 lists the fraction of surviving clusters ( $F_N$ ) and the ratio of the final to the initial mass in clusters ( $F_M$ ) for each case. For a given initial space-density, we note the relative homogeneity of the mass fractions  $F_M$  in spite of widely different initial mass spectra, the extreme values differing by a factor of 2 at most. Also, as noted by previous studies (Vesperini 1998, Baumgardt 1998, McLaughlin 1999), the evaporation and the disruption of globular clusters cannot account for the overwhelming contribution of field stars to the luminous Galactic halo. The mass of the Old Halo cluster subsystem is  $\simeq 2 \times 10^7 M_\odot$ , that is, about two per cent only of the stellar halo mass ( $\simeq 10^9 M_\odot$ , Freeman & Bland-Hawthorn 2002). On the other hand, the largest destruction rates in Table 3 ( $F_N = 0.01-0.02$ ) correspond to a total mass in survivors of order 15 to 20 per cent of the initial cluster system mass. Hence, even in this extreme case, disrupted and evaporated clusters account for 10 to 13 per cent of the stellar halo mass only.

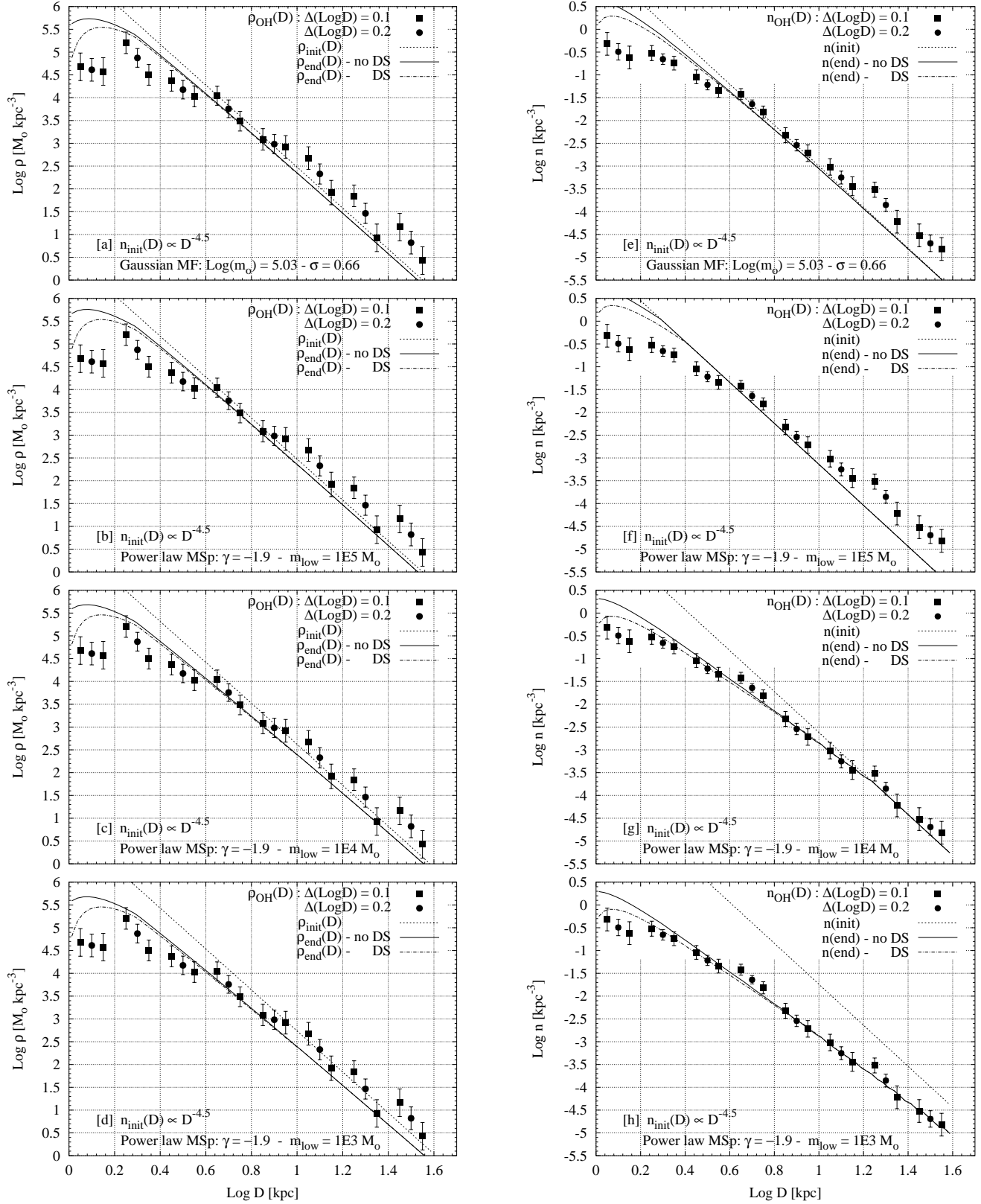
In contrast to the rather limited dispersion shown by the mass fraction,  $F_M$ , the fraction of survivors in the number density distribution  $F_N$  is characterized by a scatter as large as an order of magnitude for both initial spatial distributions. Larger destruction rates are of course achieved in case of a power-law initial mass spectrum probing down to  $1000 M_\odot$  as this one favours low-mass easily disrupted clusters. The fraction of survivors is also smaller in case of a steeper initial spatial distribution (i.e.,  $D^{-4.5}$  instead of  $D^{-3.5}$ ) since a larger fraction of globulars are then located at smaller galactocentric distances where destruction processes proceed on a shorter time-scale.

The initial (dotted curves) and evolved (solid curves: no disc shocking, dashed-dotted curves: with disc shocking) mass and number density profiles are displayed in the left and right panels, respectively, of Figs. 2 ( $n_{init} \propto D^{-3.5}$ ) and 3 ( $n_{init} \propto D^{-4.5}$ ). Examination of the left panels shows that the mass density profile  $\rho(D)$  has remained fairly well preserved during evolution for a Hubble-time<sup>3</sup>. The strongest change takes place for a power-law down to  $1000 M_\odot$ . Even in that case however, the slope of the initial distribution is reduced by  $\simeq 0.3$  only. The initial steepness of the cluster system mass density profile is thus robust, irrespective of the initial mass spectrum. In contrast, the evolution with time

<sup>3</sup> It should be kept in mind that Vesperini & Heggie's (1997) model includes a gaseous mass loss of 18 per cent fed by stellar winds. This decrease in the cluster mass is independent of galactocentric distance and, therefore, does not alter the shape of the mass density profile even though this one is reduced by the same amount.



**Figure 2.** Evolution with time of the radial mass (left panels) and number (right panels) density profiles of globular cluster systems whose initial space-density (dotted curves) obeys  $n_{\text{init}} \propto D^{-3.5}$ . Different initial distributions in mass are used, from top to bottom: a gaussian mass function  $dN/d \log m$  with a mean  $\log m_0 = 5.03$  and a standard deviation  $\sigma = 0.66$ , 3 power-law mass spectra  $dN/dm$  with a slope  $\alpha = -1.9$  and extending down to  $1E5 M_\odot$ ,  $1E4 M_\odot$  and  $1E3 M_\odot$ , respectively. Results with (dashed-dotted curves) and without (solid curves) disc-shocking are shown. The solid curves are vertically shifted in order to provide the best match to the Old Halo data

**Figure 3.** Same as in Fig. 2 but the initial space-density obeys  $n_{\text{init}} \propto D^{-4.5}$



**Table 4.** Results of fitting the radial distributions evolved over 15 Gyr to the mass and number density profiles of the Old Halo globular cluster system, for the two different bin sizes considered ( $\Delta \text{Log} D = 0.1$  or  $0.2$ ). The corresponding  $\chi^2$  and  $Q(\nu/2, \chi^2/2)$  (i.e., the goodness-of-fit) are given for each of the sixteen different cases considered

		$n_{init}(D) \propto D^{-3.5}$				$n_{init}(D) \propto D^{-4.5}$			
		$\rho(D)$		$n(D)$		$\rho(D)$		$n(D)$	
$\Delta \text{Log} D =$		0.1	0.2	0.1	0.2	0.1	0.2	0.1	0.2
G									
NoDS	$\chi^2 =$	13.05	4.53	11.84	9.40	63.49	44.79	87.48	82.56
	$Q =$	0.60	0.72	0.69	0.23	$6 \times 10^{-8}$	$2 \times 10^{-7}$	$3 \times 10^{-12}$	$4 \times 10^{-15}$
DS	$\chi^2 =$	11.13	2.32	9.97	7.27	50.79	36.11	67.35	64.51
	$Q =$	0.74	0.94	0.82	0.40	$9 \times 10^{-6}$	$7 \times 10^{-6}$	$1 \times 10^{-8}$	$2 \times 10^{-11}$
PL5									
NoDS	$\chi^2 =$	13.19	4.64	16.76	14.74	64.68	45.60	127.5	122.0
	$Q =$	0.59	0.70	0.33	0.04	$4 \times 10^{-8}$	$1 \times 10^{-7}$	$7 \times 10^{-20}$	$3 \times 10^{-23}$
DS	$\chi^2 =$	10.93	2.19	9.45	6.90	50.3	35.7	99.6	94.7
	$Q =$	0.76	0.95	0.85	0.44	$1 \times 10^{-5}$	$8 \times 10^{-6}$	$2 \times 10^{-14}$	$1 \times 10^{-17}$
PL4									
NoDS	$\chi^2 =$	13.71	4.39	42.31	37.85	51.53	35.76	25.37	23.18
	$Q =$	0.55	0.73	$2 \times 10^{-4}$	$3 \times 10^{-6}$	$7 \times 10^{-6}$	$8 \times 10^{-6}$	0.05	$2 \times 10^{-3}$
DS	$\chi^2 =$	13.15	3.00	57.97	51.88	38.55	26.76	13.73	12.73
	$Q =$	0.59	0.89	$6 \times 10^{-7}$	$6 \times 10^{-9}$	$8 \times 10^{-4}$	$4 \times 10^{-4}$	0.55	0.08
PL3									
NoDS	$\chi^2 =$	13.90	4.45	52.60	47.15	51.23	35.48	23.63	20.90
	$Q =$	0.53	0.73	$4 \times 10^{-6}$	$5 \times 10^{-8}$	$8 \times 10^{-6}$	$9 \times 10^{-6}$	0.07	$4 \times 10^{-3}$
DS	$\chi^2 =$	13.37	3.09	69.32	62.31	38.27	26.51	13.11	11.54
	$Q =$	0.57	0.88	$6 \times 10^{-9}$	$5 \times 10^{-11}$	$8 \times 10^{-4}$	$4 \times 10^{-4}$	0.59	0.12

of the number density profile is much dependent on initial conditions, as revealed by the right panels of Figs. 2 and 3. While the initial and evolved number density profiles are similar in case of a gaussian mass function (i.e., an initial mass spectrum depleted in low-mass clusters with respect to a power-law extending down to low-mass objects) or in case of a power-law mass spectrum truncated at  $10^5 M_\odot$ , the slope of the profile is reduced by  $\simeq 1$  if the initial power-law mass spectrum goes down to  $1000 M_\odot$ . Equation 2 shows that no globular clusters with masses lower than  $4000 M_\odot$  are able to survive within the outer bound of the Old Halo (say,  $D \lesssim 40$  kpc). Although these clusters represent a small fraction of the cluster system mass ( $\simeq 15$  per cent), by number, they account for  $\simeq 70$  per cent of the clusters. Hence, the destruction of these low-mass objects leads to a significantly altered number density profile while leaving the mass profile almost unaffected. Obviously, mass-related quantities are more reliable indicators of the initial conditions than are number-related quantities, especially in the case of an initial mass spectrum favouring low-mass clusters. In addition to possible slope alterations, in all cases, the spatial distribution develops a core, that is, it gets flattened in the galactocentric range 1 to 2 kpc, illustrating the larger efficiency of the disruptive processes closer to the Galactic centre.

#### 4 WHAT DENSITY PROFILES TELL US ABOUT THE GLOBULAR CLUSTER INITIAL MASS FUNCTION

In Figs. 2 and 3, the evolved spatial distributions (solid and dashed-dotted curves) have been vertically shifted in order to provide the best least-squares agreement with the presently observed distributions. The initial space-densities (dotted curves) have then been shifted accordingly. Table 4 shows the corresponding  $\chi^2$  and incomplete gamma functions  $Q(\nu/2, \chi^2/2)$  (i.e., the goodness-of-fit).

Considering the case of an initial spatial distribution scaling as  $D^{-3.5}$ , we note the excellent agreement between the evolved and observed mass density profiles, irrespective of the initial cluster mass spectrum. This is an expected result since the Old Halo mass density profile also scales as  $D^{-3.5}$  (see Table 2) and since mass profiles are fairly well-preserved in spite of the destruction of a significant fraction of the initial cluster population. Including disc shocking leads to a larger decrease in mass density at small galactocentric distance and to an even better modelling of the Old Halo profile. We note in passing that some values of the significance as measured by the incomplete gamma function are puzzlingly high, that is, larger than 0.8. It is worth keeping in mind however that the initial spatial distribution of relevance here (i.e.,  $n_{init} \propto D^{-3.5}$ ) is not that much a model but, instead, derives from a fit to the observed mass density profile for  $D \gtrsim 3$  kpc (see Table 2). These high  $Q$  values thus

illustrate furthermore that the evolved mass density profile mirrors faithfully the initial one.

As for the evolved number density profile, this agrees with the data only if the globular cluster system started with either a gaussian mass function or a power-law mass spectrum truncated at  $10^5 M_\odot$ . In case of a power-law mass spectrum probing down to low cluster mass, the  $Q$  values get extremely low, disproving such initial mass spectra. This discrepancy results from the sharp change experienced by the slope of the number density profile (panel [h] in Fig. 2), leading to a present steepness significantly shallower ( $\simeq -2.5$ ) than the observed one ( $\simeq -3.5$ , see Table 2). As a result, examination of Fig. 2 and Table 4 shows that the comparison of the evolved (i.e., modelled) and observed radial density profiles, *in terms of mass as well as in terms of number*, enables us to constrain the initial mass spectrum of globular clusters. The  $Q$  values strongly favour either an initial gaussian mass function or a power-law with slope of order  $-1.9$  and truncated at large mass, around  $10^5 M_\odot$ , that is, an initial mass distribution which is somehow depleted in low-mass objects. In this respect, our results confirm those achieved by Vesperini (1998).

We now consider the steeper initial spatial distribution, namely  $n_{init} \propto D^{-4.5}$ . As already suggested by Baumgardt (1998), there is an excellent agreement between the halo number density profile and its modelled counterpart in the case of a power-law extending down to  $1000 M_\odot$ , especially if disc shocking is taken into account. Owing to the large contribution of low-mass clusters, the initially steep profile is turned into a shallower one, thus matching the halo  $-3.5$  slope. However, we caution that the evolved mass density profile does not fit its Old Halo counterpart convincingly in any case. The best match is obtained for a globular cluster system with a power-law initial mass spectrum probing down to low-mass (see Table 4). Even though such a possibility cannot be ruled out firmly, the goodness-of-fit is very marginal ( $Q \lesssim 0.001$ ). This case is therefore much less likely than the one we have previously discussed, namely, a globular cluster system whose initial spatial steepness is similar to the present one.

Baumgardt (1998) himself noted the oddity of this result as it implies a discrepancy between the initial slope of the globular cluster spatial distribution on the one hand and the steepness of the stellar halo density profile on the other hand. Indeed, the space-density of halo RR Lyrae (Suntzeff, Kinman & Kraft 1991) as well as of halo blue horizontal branch stars (Kinman, Suntzeff & Kraft 1994) falls off as  $D^{-3.5}$ . Baumgardt (1998) suggests that this discrepancy results from a varying star cluster to field star formation efficiency. Considering the  $Q$  values listed in Table 4, a much safer conclusion may be that the globular cluster system started with a space-density scaling as  $D^{-3.5}$  coupled with either a gaussian mass function or a power-law truncated at  $10^5 M_\odot$ .

While our simulations start with many thousands of clusters, the survival rates  $F_N$  quoted in Table 3 indicate that the initial number of clusters is on the order of that today in case of a gaussian initial mass function or in case of a power-law mass spectrum truncated at  $10^5 M_\odot$ . As for the gaussian initial mass function, we have checked that an

initial total number of clusters of 200 only does not introduce a significant scatter in the evolved mass density profile with respect to the size of the error bars. Using Vesperini & Heggie's (1997) model with disc shocking and considering a slope  $\gamma = -3.5$  for the initial radial distribution, the incomplete gamma function for the evolved mass density profile ( $\Delta \log D = 0.2$ ) ranges from 0.3 up to 0.9 (10 random samplings of the gaussian cluster IMF). We note that these results are obtained in case of a gaussian truncated at  $1.5E6 M_\odot$  in order to avoid the presence of clusters significantly more massive than is observed today. Actually, inspection of the luminous mass estimates of the halo globular clusters shows  $10^6 M_\odot$  to be an upper limit to the present-day globular cluster mass. More massive clusters do actually exist, e.g.,  $\omega$  Cen, M54 (=Sagittarius core), NGC 2419 and a few disc clusters, but none of them are relevant to the present study. Running the same simulations in case of a non-truncated gaussian, the incomplete gamma function tends to get smaller (i.e., down to 0.002 in one case). This is due to the occasional sampling of very massive (i.e.,  $> 1.5E6 M_\odot$ ) clusters, giving rise to an upwards scatter in the outermost least-populated bins of the mass density profile.

As for the case of a power-law mass spectrum truncated at  $10^5 M_\odot$ , we have evolved a cluster system initially comprising 150 clusters only. The incomplete gamma function for the evolved mass density profile ranges from 0.01 to 0.7 (10 random realisations, of which 8 give  $Q > 0.1$ ). This robustness, despite a limited number of clusters, is due to the narrow mass range associated to the truncation at large cluster mass.<sup>4</sup>

In fact, our results are reminiscent of those obtained by Vesperini (2000, 2001) in the case of globular cluster systems hosted by elliptical galaxies. Investigating the case of a power-law initial mass spectrum extending down to low-mass combined with a coreless  $D^{-3.5}$  initial number density profile, Vesperini (2001) noted that the evolutionary processes produce a significant dependence of the average cluster mass on the galactocentric distance in the sense that clusters located in the inner galactic regions are more massive. This dependence is equivalent to the difference between the slopes of the evolved mass and number density profiles highlighted in the bottom panels of Fig. 2. Vesperini's (2001) result contrasts with several observational studies that fail to find a significant radial gradient of the average cluster mass within elliptical galaxies (e.g., M87, Kundu et al. 1999). Conversely, Vesperini (2000) emphasized that, in the case of a gaussian initial mass function, the radial gradient of the average cluster mass is weak and consistent with

<sup>4</sup> In case of a power-law initial mass spectrum extending down to  $1000 M_\odot$ , the globular cluster system initially hosted several thousands of clusters and the small-number sampling thus does not constitute an issue. Should the initial number of clusters be on the order of that today (say, 100), the evolved population would contain just a very few survivors, possibly none at all since the selection of low-mass clusters would be favoured owing to the small-number sampling. Actually, following a Hubble-time of evolution, the number of survivors is in the range [2,10] ([0,4]) if the slope of the initial radial distribution is  $-3.5$  ( $-4.5$ ) (10 random realisations), leading to a discrepancy with the present-day cluster number.

the observations. Equivalently, the evolved mass and number density profiles match each other, as shown by the top panels of Fig. 2.

The marked evolution of the number density profile with respect to the mass density profile in the case of a power-law mass spectrum arises because, as Vesperini (1998, 2000, 2001), we have assumed that clusters are orbiting at constant galactocentric distance. Should a substantial radial mixing take place, a more radially uniform mass function may emerge. We have thus tested whether our results are significantly affected if the orbital eccentricity is  $e = 0.5$ . According to Baumgardt & Makino (2003), the lifetime of a cluster on an orbit with eccentricity  $e$  is decreased by a factor  $(1 - e)$  with respect to a cluster on a circular orbit with a radius similar to the apogalactic radius of the eccentric orbit. Considering the two extreme (and key) cases, namely, the gaussian [G] and power-law [PL3] initial cluster mass distributions, combined with a coreless  $D^{-3.5}$  initial number density profile, we have run additional simulations in which the quantity  $F_{cw}$  (equation 3) is halved (i.e., multiplied by  $1 - e$ ). The corresponding evolved mass and number density profiles are in remarkable agreement with those derived under the assumption of circular orbits. The only significant difference is the destruction of all the clusters confined within 1.2 kpc from the Galactic centre if  $e = 0.5$ . The comparison between the predicted profiles and the Old Halo distributions leads to (considering  $\Delta \log D = 0.2$ ):

(i) for a Gaussian initial mass function [G]:  $Q=0.03 [\rho(D)]$  and  $Q=0.003 [n(D)]$  for the mass and number density profiles, respectively;

(ii) for a power-law initial mass spectrum [PL3]:  $Q=0.005 [\rho(D)]$  and  $Q=10^{-16} [n(D)]$ .

As for the gaussian mass function, the incomplete gamma function is smaller than that derived for circular orbits (Table 4). Yet, this effect is mostly driven by the first bin, this being located on the edge of the region of complete cluster destruction (i.e.,  $D \simeq 1.2$  kpc). We note that the power-law initial mass spectrum [PL3] is again rejected by the poor agreement between the predicted and observed number density profiles (that is, the increase in the mean cluster mass with decreasing galactocentric distance is much larger than is observed). This result is not unexpected. The evaporation rate of a cluster with a given mass depends on its orbit, especially its pericentre (see e.g., Baumgardt 1998). Considering a system of clusters extending up to 40 kpc from the Galactic centre, if  $e=0.5$ , the range of perigalactic distances is  $\simeq 1$ -13.3 kpc. The lack of consistency between the slopes of the evolved mass and number density profiles in the [PL3] case illustrates that such a range of perigalactic distances is still too large to erase radial variations in the mean cluster mass. As demonstrated by Fall & Zhang (2001), a narrow distribution of pericentres and, thus, disruption rates almost independent of the cluster galactocentric distance, can be achieved if the initial velocity distribution shows some radial anisotropy *and* the radial anisotropy is increasing outward. Should such conditions be satisfied, the mean cluster masses in the inner ( $D < 5$  kpc) and outer ( $D > 5$  kpc) groups of clusters are similar. However, that result is obtained in the case of an initial Schechter mass spectrum (i.e.,  $dN/dm \propto m^{-2} e^{-m/5 \times 10^6 M_\odot}$ ), i.e., a mass distribution steeper than a power-law  $\alpha = -2$ . In the case

of an initial power-law mass spectrum, the evolved mass distribution fails to reproduce the high mass-regime of the present-day distribution (Fall & Zhang 2001, their Fig. 3). A radially uniform cluster mass function can thus be achieved even if the initial mass distribution is steadily rising toward low-mass, although such a solution requires appropriate tuning.

## 5 SUMMARY AND CONCLUSIONS

The initial distribution in mass of the Galactic halo globular clusters has so far remained a poorly-known function. This is due to the fact that both a gaussian initial mass function (i.e., a two-index power-law mass spectrum) and a power-law initial mass spectrum evolve into the presently observed bell-shaped cluster mass function. As a result, the study of the temporal evolution of the mass function/spectrum only does not enable one to assess how large was the contribution of low-mass (say a few thousand solar masses) objects to the initial population of clusters.

In this paper, we have proposed a new method for shedding light on this issue which consists in comparing globular cluster system density profiles with their modelled counterparts, as a function of mass density as well as a function of number density. We assume, as in previous studies of globular cluster system dynamical evolution, that the cluster mass range and the cluster mass spectrum are initially independent of their galactocentric distance. This is equivalent to assuming that the initial mass and number density profiles are identical in shape. On the other hand, the present mass and number density profiles of the Old Halo are alike as well (see Section 2). The new constraints on the initial globular cluster mass function we have derived arise from combining this widespread assumption and this observational fact.

The clusters most vulnerable to evaporation and disruption are the low-mass ones as well as those located at small galactocentric distance. In other words, the disruption rate of globular clusters depends on their initial distribution in space as well as on their initial distribution in mass. The key point is that the mass and number density profiles show contrasting temporal evolutions. While the evolution of the latter is heavily driven by the initial cluster mass spectrum, the former remains almost unchanged during evolution for a Hubble-time, providing always that the Galactic potential remains smooth and was slowly varying. Hence, the robustness of the mass density profile provides us with an immediate estimate of the initial steepness of the spatial distribution. This can then be evolved for various initial cluster mass spectra and the resulting number density profiles compared to the observed one in order to discriminate which cluster mass spectrum provides the best match between the data and the model.

In order to test this idea, we have evolved various putative globular cluster systems characterized by different combinations of initial number density profiles (i.e., how clusters are distributed in space) and initial mass spectra (i.e., how clusters are distributed in mass). Results of these simulations are displayed in Figs. 2 and 3. We have shown that, irrespective of the initial globular cluster mass spectrum, the damage performed to the initial mass content in clusters is limited to one effective radius, that is,  $D \lesssim 3$  kpc (see also

McLaughlin 1999). While in this range, the spatial distribution of the cluster system mass flattens owing to the greater efficiency of cluster destruction processes, the overall slope remains close to its initial value. In sharp contrast, the temporal evolution of the number density profile depends sensitively on the initial mass spectrum. The steepness of the space-density is stationary in case of a gaussian mass function or of a power-law truncated at  $10^5 M_\odot$ . On the other hand, it gets significantly shallower in the case of a mass spectrum favouring low-mass clusters, e.g., a power-law extending down to  $10^3 M_\odot$ .

For each simulation, we have compared in a least-squares sense the presently observed spatial distributions with the modelled ones, obtaining the  $\chi^2$  and the incomplete gamma function measure of probability (see Table 4). The most likely initial conditions of course correspond to the cases for which the evolved mass *and* number density profiles are in good agreement with their Old Halo counterparts. The best match is achieved when an initial spatial distribution with a slope of  $-3.5$  is combined with an initial mass spectrum depleted in low-mass clusters, that is, either a gaussian mass function or a power-law mass spectrum truncated at  $10^5 M_\odot$ . In this case, the cluster destruction rate is limited, as also is the corresponding temporal evolution of the number density profile, thus preserving its initial  $-3.5$  steepness, in agreement with what is observed for the Old Halo (see Table 2). If the Galactic halo globular cluster system had actually started with this initial spatial distribution, it is very unlikely that the initial mass spectrum was a pure power-law extending down to  $1000 M_\odot$ . The abundance of low-mass objects in such a globular cluster system would make the number density profile shallow with time, making it unable to fit the present  $-3.5$  slope.

We confirm Baumgardt's (1998) finding following which a power-law probing down to  $1000 M_\odot$  combined with a steep (i.e.,  $\gamma = -4.5$ ) spatial distribution leads to good agreement with the observed present-day number density profile. However, we caution that the observed mass density profile is then not well fitted by its evolved counterpart. In fact, owing to their robustness, all the evolved mass density profiles, irrespective of the initial globular cluster mass spectrum, are locked close to their initial  $-4.5$  slope. As a result, they remain significantly steeper, even after a 15 Gyr long evolution, than the  $-3.5$  slope shown by the present spatial distribution of the Old Halo cluster system mass. Even though such a possibility cannot be firmly ruled out ( $Q \lesssim 0.001$  if disc shocking is included in the simulations), it remains much less likely than the initial  $D^{-3.5}$  space-density which we have just discussed. As a result, although the number density profile alone indicates that the Galactic globular cluster system may have started with a very steep initial spatial distribution and a power-law mass spectrum covering three orders of magnitude in mass, the mass density profile tends to dismiss this possibility.

All together, our results support the hypothesis following which the Galactic halo globular cluster system started with an initial space-density scaling as  $D^{-3.5}$  and an initial mass spectrum somehow depleted in low-mass clusters, that is, a bell-shaped mass function similar to the current one, or a power-law mass spectrum truncated near  $10^5 M_\odot$ .

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